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Final Report on Instrumentation and Equipment Upgrades to Improve Acoustical and Fluid Dynamic Measurements in the Garfield Thomas Water Tunnel

By

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14. ABSTRACT

The overall objective of the project was to plan and implement the necessary Garfield Thomas Water Tunnel mechanical, electrical, and instrumentation upgrades to support R&D for the next generation platforms and propulsors. However, in order to appropriately assess designs intended to meet the future hydrodynamic and acoustic goals, additional improvements in tunnel quieting and unsteady flow and acoustic signal processing were required. In addition, improved accuracy and resolution were needed for validation of design tools that will allow "out of the box" design tradeoffs at the small computational resolutions necessary for acoustics. This report describes the systems acquired under the grant.

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Subject: *Final Report on Instrumentation and Equipment Upgrades to Improve Acoustical and Fluid Dynamic Measurements in the Garfield Thomas Water Tunnel*

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Abstract: The overall objective of the project was to plan and implement the necessary Garfield Thomas Water Tunnel mechanical, electrical, and instrumentation upgrades to support R&D for the next generation platforms and propulsors. However, in order to appropriately assess designs intended to meet the future hydrodynamic and acoustic goals, additional improvements in tunnel quieting and unsteady flow and acoustic signal processing were required. In addition, improved accuracy and resolution were needed for validation of design tools that will allow "out of the box" design tradeoffs at the small computational resolutions necessary for acoustics. This report describes the systems acquired under the grant.

Acknowledgements: This work was performed under ONR grant N00014-01-1-0311, The ONR Project Officer was Dr. Patrick Purtell, ONR 333.

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Figure C-3. DPIV measured color contour map of the turbulent boundary layer on the cylindrical microbubble body.

1.0 Overall Goals

This report documents work performed under ONR grant N00014-01-1-0311, INSTRUMENTATION AND EQUIPMENT UPGRADES TO IMPROVE ACOUSTICAL AND FLUID DYNAMIC MEASUREMENTS IN THE GARFIELD THOMAS WATER TUNNEL. The overall objective of the project was to plan and implement the necessary Garfield Thomas Water Tunnel mechanical, electrical, and instrumentation upgrades to support R&D for the next generation platforms and propulsors. Existing instrumentation had been adequate for testing of current designs. However, in order to appropriately assess designs intended to meet the projected future hydrodynamic and acoustic goals, additional improvements in tunnel quieting and unsteady flow and acoustic signal processing were required. In addition, improved accuracy and resolution were needed for validation of design tools that will allow "out of the box" design tradeoffs at the small computational resolutions necessary for acoustics.

2.0 Background

Major improvements to the hydrodynamic and hydroacoustic data acquisition and reduction infrastructure at the Garfield Thomas Water Tunnel of the Applied Research Laboratory have occurred at approximately 10 year intervals. In 1982, the Data Acquisition Data Reduction (DADR) system based on a central Digital VAX computer was developed using IEEE 488 communication between data acquisition devices. An effort was begun in 1990 to replace this system with a more distributed acquisition capability using the emerging VXI bus standard and ethernet communication between computers [1]. These upgrades generally coincided with major design and evaluation periods for submarine propulsor programs.

Assessments of 48-inch Water Tunnel acoustic background levels and signal processing have been performed on a continuing basis. Some of these have been documented as shown in references [2] through [6]. A major look at an alternative downstream array was done in 1994 [7]. Many of the desired improvements have not been economically feasible (particularly in computer processing power) until recently. A consultant, Allan Piersol, provided a more recent evaluation [8] for ARL.

A computational and experimental resources cost center was established for the divisions in the G. Thomas Water Tunnel building in 1998. The fees generated provide for the periodic replacement of the computers needed for both computational efforts and experimental data acquisition and analysis. Likewise, some minor data acquisition and water tunnel mechanical and electrical components are maintained using these funds. However, these resources are insufficient to perform some of the critical maintenance and upgrades. Therefore, a proposal was developed that led to this grant award by ONR.

3.0 Technical Objectives and Approach

This project covers material and equipment enhancements to the Garfield Thomas Water Tunnel of the Applied Research Laboratory. These enhancements focused on three areas which needed to be simultaneously improved in order to perform high quality evaluations of future fluid dynamic and hydroacoustic developments to meet the demanding acoustic and hydrodynamic performance requirements. The improvements were prioritized in each area such that the A items in each area should all be pursued in order to optimize the improvements. The desired upgrades were grouped into improvement objective areas and usually consisted of a phased approach to implementing the ultimate system. The tunnel mechanical and electrical maintenance needs impact all testing and were addressed as a high priority.

Historically, a combination of Laboratory overhead and fee funds and project funds have financed improvements. To maximize the benefit of this grant, the manpower to complete noise source assessments, purchase selections, and implementation were funded by ARL Penn State.

Each improvement area had a technical leader assigned to complete the implementation and performance assessment plan for that area. This included collecting and assessing any additional diagnostic data, writing of performance specifications for the equipment to be purchased, evaluation and selection of equipment, coordination of installation, and performance testing. These plans were reviewed and approved by the principal investigators and the technical division heads.

The approach taken to evaluate the acoustic measurement performance in the water tunnel is to perform an analysis with the passive sonar equation and determine the "minimum measurable source levels" (reference [4]). We can mostly affect array gain, background noise level, and detection threshold. The described improvements were meant to benefit both broadband and narrowband analysis.

3.1 Specific Proposed Enhancements

3.1.1 Water Tunnel Physical Plant

The 48-inch water tunnel has been in constant use since 1950 and only maintenance repairs have been made except for a drive system overhaul and upgrade in 1989. It became necessary to replace or refurbish many of the supporting pumps, tunnel windows used for visualization and cavitation viewing, and upgrade the electrical distribution system and model motors to instrumentation quality. The upgrades done by this project insure the efficient operation of the physical plant and are necessary to significantly reduce the electrical noise floor of the tunnel instrumentation.

1A	pumps, compressors, seals	\$ 158,467
1B	tunnel windows	\$ 13,329
1C	low noise model motors and drive	\$ 120,000
1D	electrical distribution upgrade to reduce electromagnetic interference	\$ 127,336

(The costs reflect the original proposal amounts. The actual expenditures are shown in later tables. The letters indicate priority order.)

3.1.2 Acoustic Arrays and Acoustic Processing

The current propulsor noise levels are near the floor of the current acoustic processing system which has been in operation since the 1970's with minor improvements. Significant improvements have been made in beamforming and processing techniques. These are necessary to make acoustic measurements for future propulsors that will meet the projected acoustic goals.

2A	replacement array elements	$ 59,240
2B	Acoustic Processing System	$ 133,000
2C	noise and vibration monitoring sys	$ 170,303

3.1.3 Advanced Instrumentation, Data Acquisition, and Calibration Equipment

The water tunnel has traditionally been utilized to support propulsor development and S&T experiments. However, it now must also provide validation quality experimental data to support computational modeling and simulations. This requires the measurement of time-dependent flows, full-field flow measurements, and multi-point correlations with well defined uncertainty analyses. This requires new optical measurement instrumentation to eliminate electrical interferences, fiber optic instrumentation with optical analysis capabilities, faster sampling hardware, software, and manipulation of higher volumes of data, and enhanced calibration capabilities.

3A	particle image velocimetry and laser Doppler velocimetry upgrades	$ 98,101
3B	optical data path and data collection	$ 50,700
3C	data acquisition hardware / software	$ 110,163
3D	sensor calibration hardware	$ 70,711

3.2 Schedule and Costs

During FY 01, the following enhancements were to be made and evaluated:

1A pumps, compressors, seals
1B tunnel windows
1C low noise model motors and drive
2A replacement array elements
2B acoustic processing system
2C noise and vibration monitoring sys
3A particle image velocimetry and
   laser Doppler velocimetry upgrades
3D sensor calibration hardware

TOTAL FY01 $ 600,000

During an option year in FY 02, the remaining enhancements were proposed to be made and evaluated:

1A	pumps, compressors, seals
1D	electrical distribution upgrade to reduce electromagnetic interference
2C	noise and vibration monitoring sys
3B	optical data path and data collection
3C	data acquisition hardware / software
3D	sensor calibration hardware

TOTAL FY02 $ 600,000

Details on the actual purchases and costs are provided in Appendix A. $578K out of $600K was spent directly on hardware with $22K spent of grant administration.

4.0 Upgrades Completed

Each improvement area had a technical leader assigned to complete the implementation and performance assessment plan for that area. This included collecting and assessing any additional diagnostic data, writing of performance specifications for the equipment to be purchased, evaluation and selection of equipment, coordination of installation, and performance testing. These plans were reviewed and approved by the principal investigators and the Fluids and Structural Mechanics Office technical division heads.

The evaluation process began in February 2001 with implementation and testing completing in 2002. Labor for the upgrades was funded by ARL. Some supplemental hardware was purchased by the FSMO Computational and Experimental Resources cost center.

4.1 Water Tunnel Physical Plant

- Driveshaft seals upgraded ($1,582) [All costs shown include applicable overhead charges.]
- High Reynolds Number Pump Facility (HIREP) bearings, seals, and slip rings upgraded ($5,606)
- New piping and installation of a second water fill pump to decrease fill times. ($23,706)
- The air compressor used to supply tunnel control system pneumatic air was upgraded.
- Overhaul and upgrade of the tunnel bay crane for moving models and tunnel hatch. ($45,848)
- Tunnel test section side windows replaced to provide improved visual access. ($14,205)
- An extensive investigation was made into the sources of electrical noise contaminating specific water tunnel measurements. A significant source of tonal harmonics is due to the six step inverter powering the model motors. A new filter was evaluated with an inverter on the recently developed ARL Penn State Pump Test Loop to determine the noise reduction possible from filtering alone. The results were not significant enough to commit to its use alone in GTWT. A motor generator system was determined to be the best solution for reduction of electrical noise in models with internal motors.
- A motor generator was specified and procured that will accommodate low RPM, high torque propulsor designs. ($81,480)

Evaluations have been conducted on inverter and electrical distribution noise that can contaminate sensor signals. A new filter was evaluated with an inverter on the ARL Penn State Pump Test Loop to determine the noise reduction possible from filtering alone. The results were not significant enough to commit to its use alone in GTWT. A motor generator system is still believed to be the best solution for reduction of electrical noise in models with internal motors. Details of assessing the need for the motor generator are provided in Appendix B.

Several upgrades were made to ancillary machinery:

- HIREP bearings and seals
- Piping and installation for second fill pump
- Air compressor refurbishment
- Bay crane overhaul and certification
- GTWT main driveshaft seals
- Test section windows and window frames
- Tunnel pressure controller

Some of these improvements are pictured below.

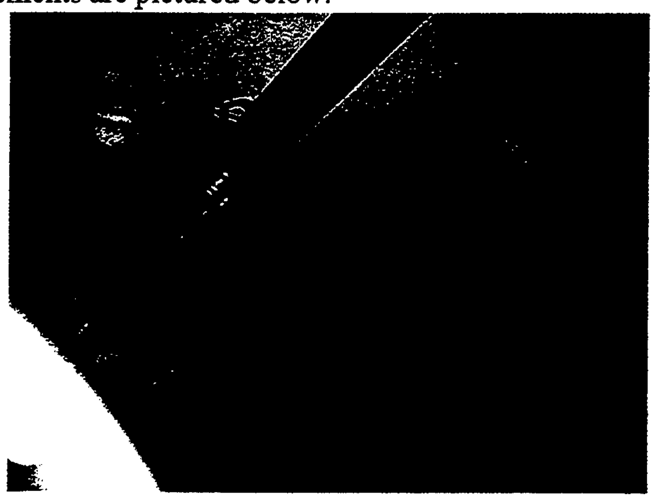


Figure 1. Piping installed for second fill pump.

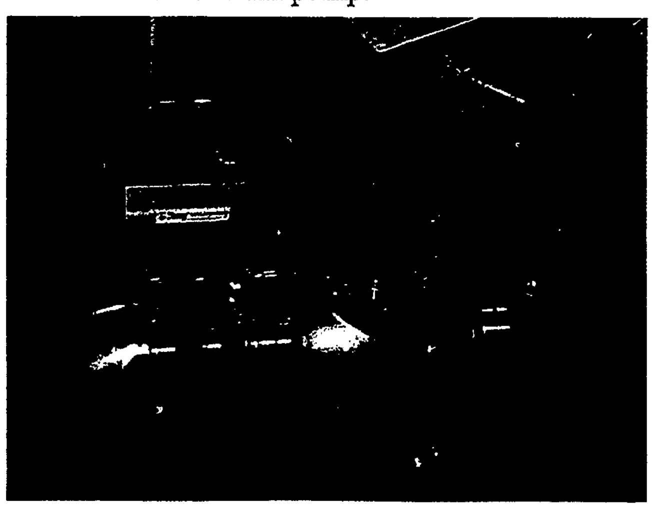


Figure 2. Control valves installed for second fill pump.

Figure 3. Second fill pump.

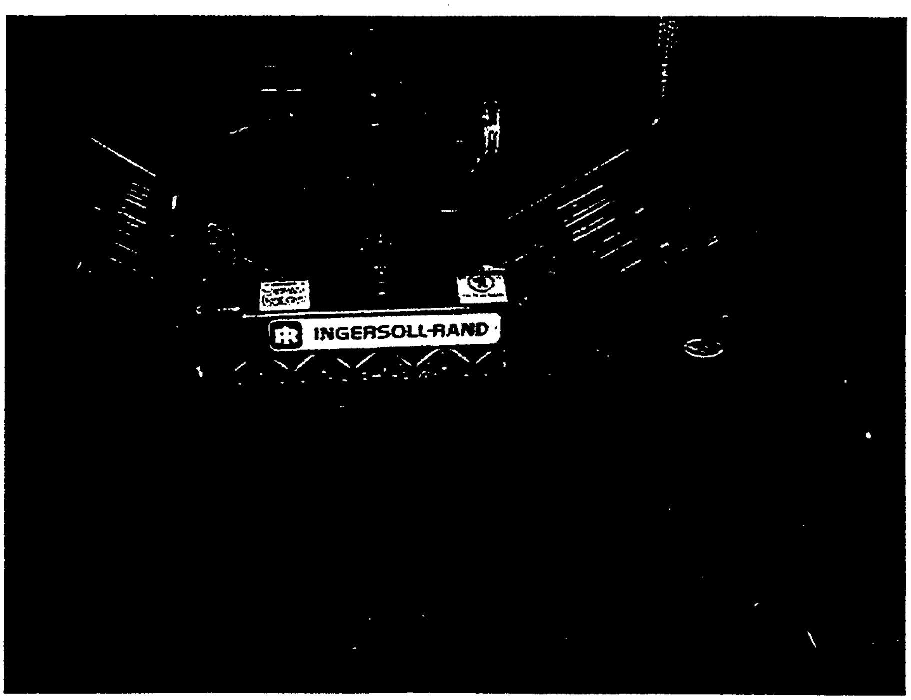
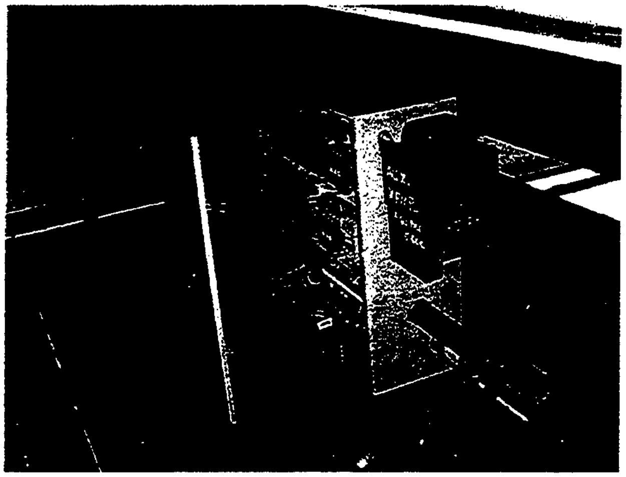


Figure 4. Upgraded air compressor for tunnel control air.



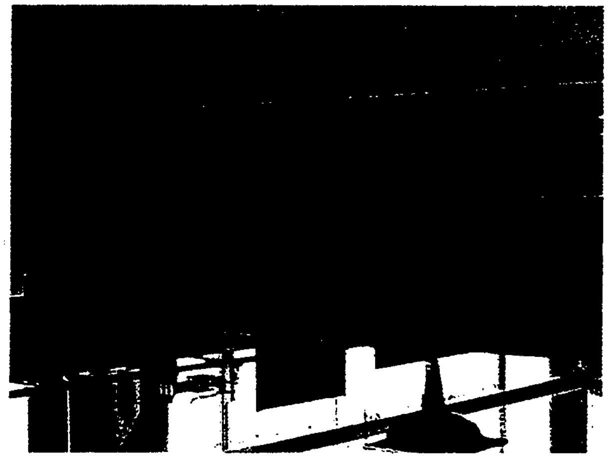


Figure 5. Refurbished overhead crane electrical cabinet.

Figure 6. Overhead crane serving 48-inch water tunnel and rewound motor.

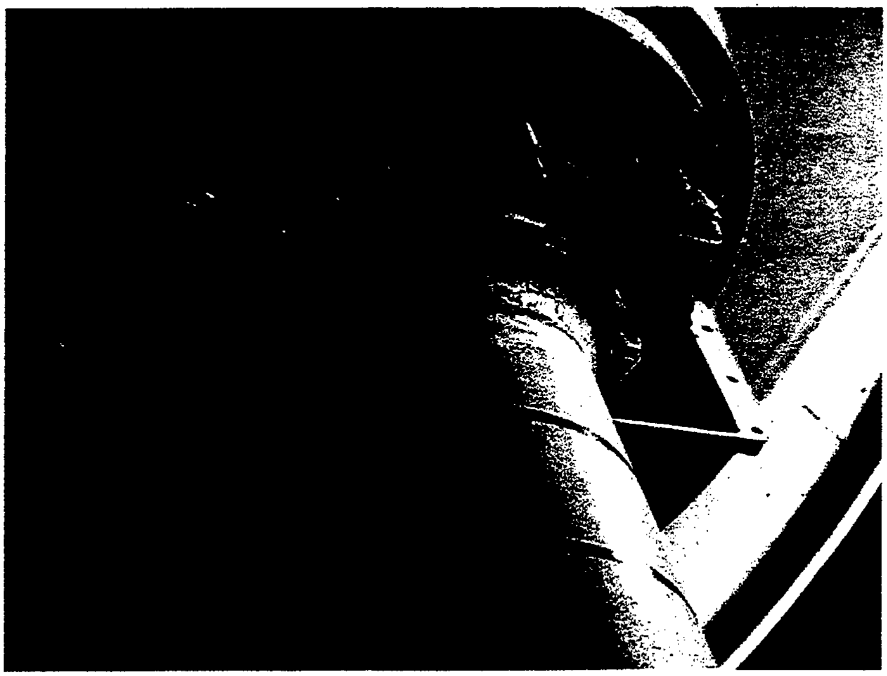


Figure 7.   Refurbished main shaft seals.

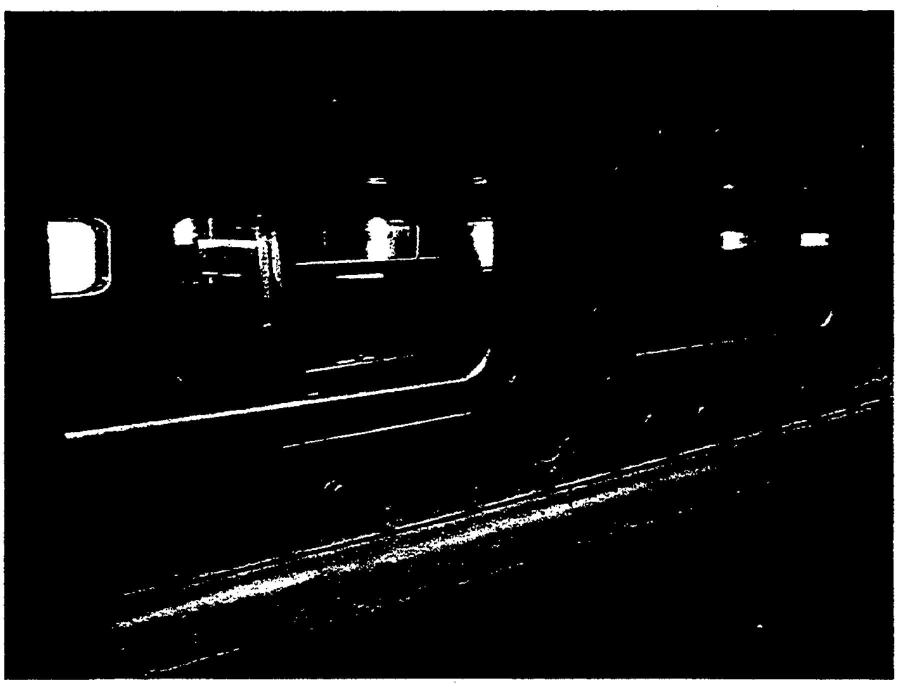


Figure 8.   New test section windows.

Figure 9. Setra tunnel pressure controller.

The upgrades are not glamorous but they have resulted in safer and more efficient testing.

4.2 Acoustic Array and Acoustic Processing

- The data acquisition workstation for the acoustic processing system was received and shipped to LMS North America for integration with the data acquisition hardware and processing software. ($7,581)

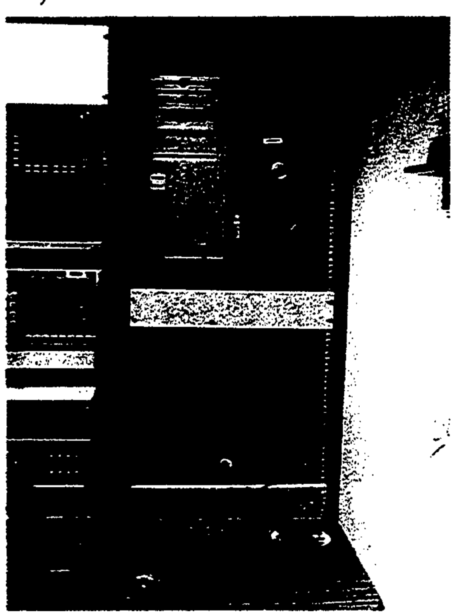


Figure 10. Dell workstation for acoustic processing.

- An extensive analysis was performed on the efficacy of beamforming versus array design as applied to the passive sonar equation application to the water tunnel acoustic data acquisition. A beamformer system was specified from ICS. However, consideration of the capabilities of a new multichannel dynamic signal analysis system as described below was determined to provide a greater improvement in SNR.

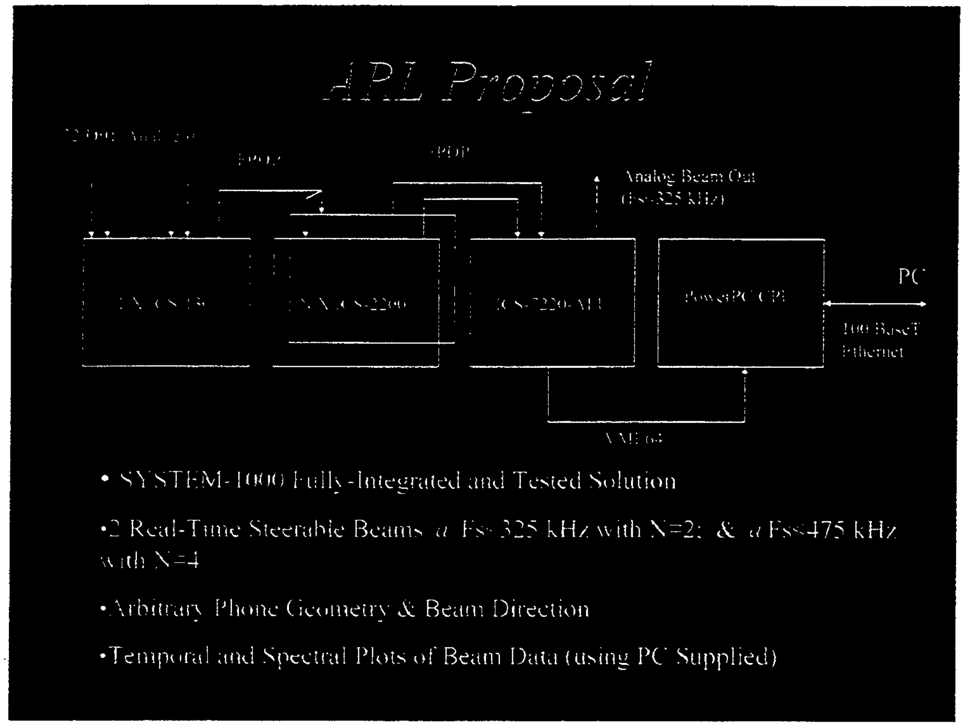


Figure 11. Block diagram of proposed beamformer system from ICS.

- Replacement of the downstream array in the water tunnel evolved into a competition of array designs with the options being a planar array, a cruciform array, and a conical array concept. EDO Ceramic, ITC, NUWC NPT and ARL Penn State all competed against a RFP and performance specification written to ensure meeting future anticipated acoustic goals and performance requirements. The current array is limited in low and high frequencies because it was designed for a 5 – 40 KHz optimum range. The in-house array design was selected for best performance and cost effectiveness. The new array will be passive only and will have a considerably wider optimum receive response and potential for better directivity. Additional design features include low noise preamplifiers and better electrical shielding. ($97,054) This is described extensively in reference [9]. An example of one of the processing boards developed is shown in figure 12.

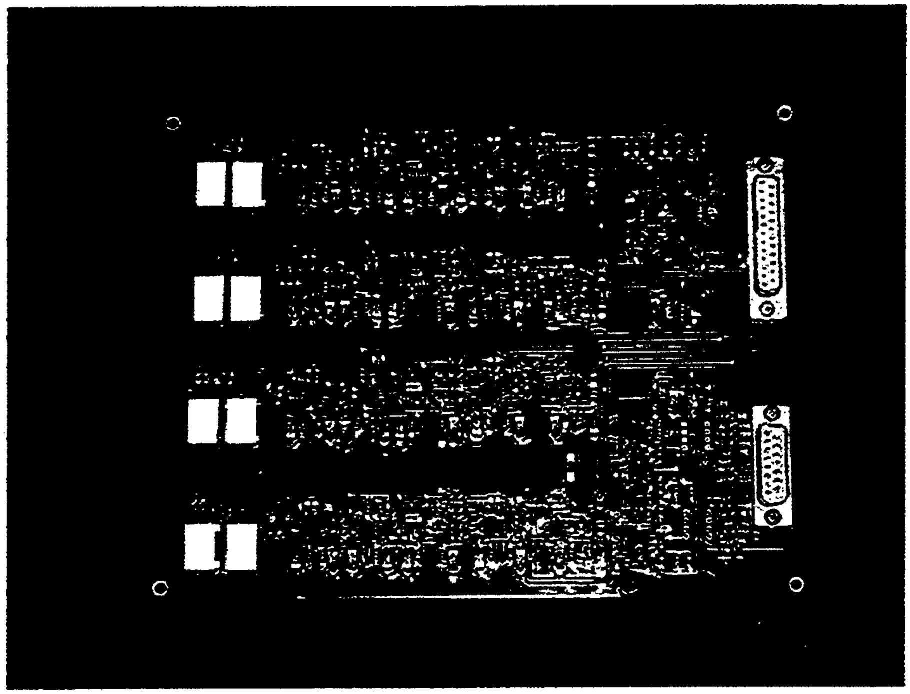


Figure 12. Signal processing board for new downstream acoustic array.

The replacement downstream array was designed, fabricated and tested at ARL Penn State. It consists of four concentric, planar ring elements configured as a broadband receive array. The new array (ARL no. 02-16) provides a substantially larger operating frequency band (0.5 to 200 kHz) than the previous one (5 to 40 kHz and 60 to 80 kHz). The array is fabricated from 1-3 composite material and has four separate ring channels plus a sum (all four rings) channel. The free field sensitivity of the array is flat above 4 kHz. Below 4 kHz, the free field sensitivity shows variability of up to 10 dB due to resonances in the mounting plate. Amplitude shading is incorporated to provide low sidelobe levels that are typically more than 30 dB down. The array and preamplifier exhibit very low noise levels for the sum channel over the majority of the operating band.

In the array design and implementation, two sources of unwanted noise were addressed; flow noise over the array and electromagnetic interference (EMI). The flow noise over the array was addressed in the same fashion as for the previous array; the array is housed in a low noise headform and mounted in the water tunnel diffuser such that the velocity over the nose is lower than that in the water tunnel test section.

Great care was taken to incorporate electrical noise control features into the array design. First and foremost of these features is the EMI shielding of the array elements. This shielding is achieved by encapsulating the elements in copper-plated Kapton and then connecting this shield to electrical ground (figure 13). EMI also contaminates the noise floor of the array through the signal lines serving as antennas. The new array design combats this contribution to the unwanted noise in two ways. The first is by shortening the cable length from the array elements to the preamplifier by placing the preamplifier in the array housing. This step is crucial to controlling the EMI contamination because the voltage level of the signal is lowest prior to the preamplifier. The antenna effect is reduced on the array output cables outputting the signal in true differential format. When the high and low side of the differential signal are recombined, the electrical noise contributions injected on the cable between the preamplifier and the measurement system cancel out.

This new receive array with its greatly enhanced frequency range, low noise, flat sensitivity and EMI noise reduction features has greatly improved the ability to make radiated noise measurements in the 48-inch water tunnel. It is now possible to develop reasonable sensitivity calibrations with much less dynamic range issues over a broader frequency spectrum. This means that fewer measurements need to be performed over multiple limited frequency ranges in order to assemble the entire signature spectrum. Current measurements are now valid in several more octave bands. It is now also much easier to recognize spatial mode influences on the measurements.

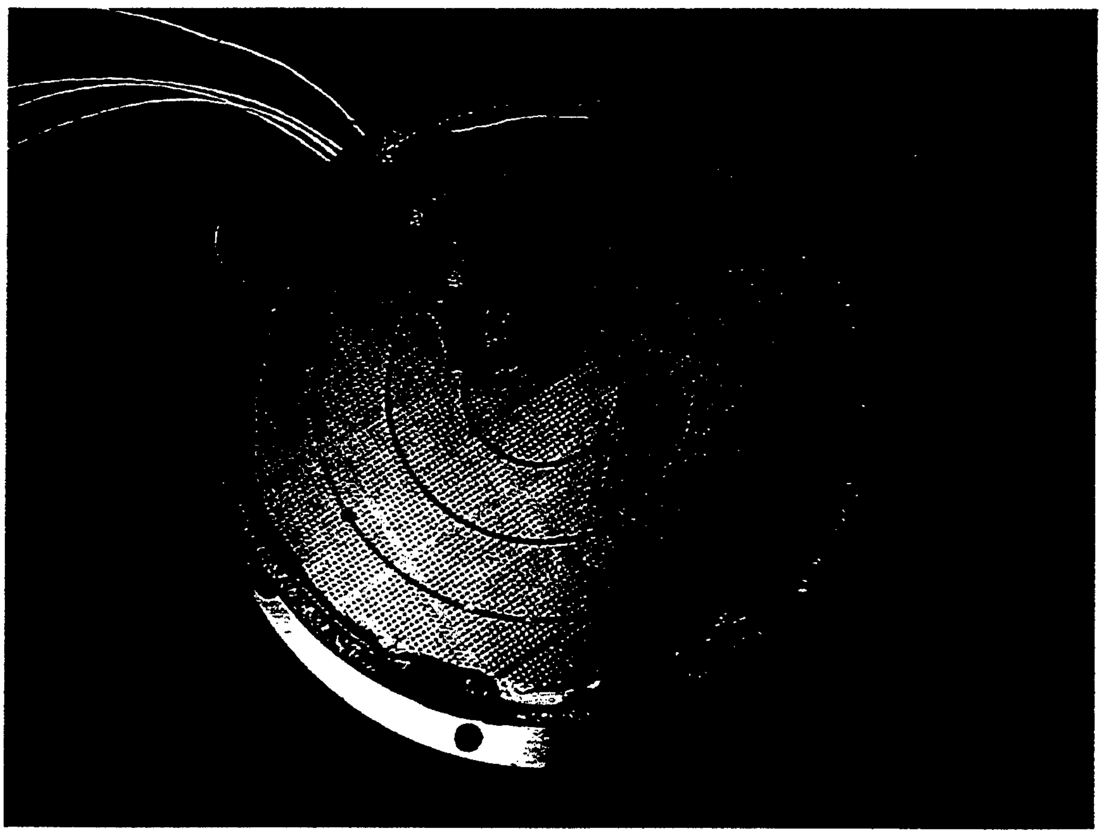


Figure 13. Downstream array after bonding phase of construction.

- An extensive analysis and competition was held with LMS International, Bruel & Kjaer, Spectral Dynamics, and Data Physics to choose a multichannel signal processing system to replace the Zonic systems purchased in 1989. In-house demonstrations were performed and multiple meetings were held with the two primary competitors, LMS and B&K. The LMS system was finally selected and was delivered January 2002 ($99,747)

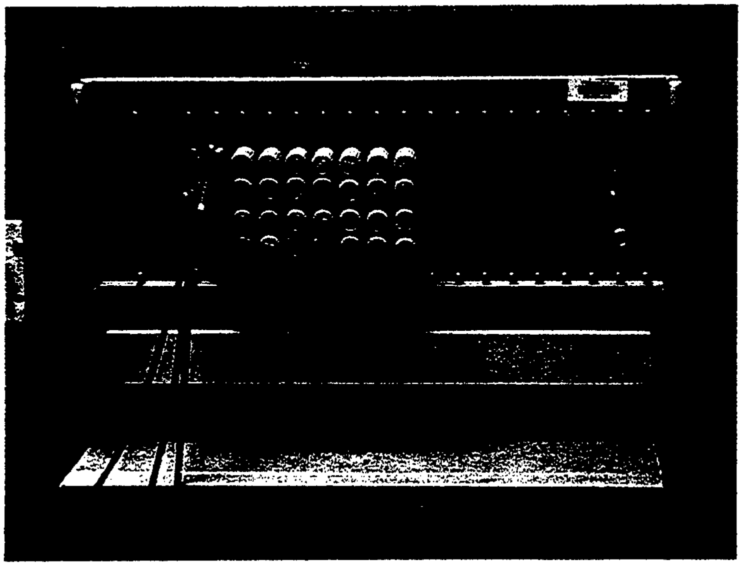


Figure 14. LMS multichannel signal processing front end hardware.

4.3 Advanced Instrumentation, Data Acquisition, and Calibration Equipment

- The major enhancement was the purchase of a stereo particle image velocimetry (PIV) system from TSI, Inc. It includes a mini dual Nd:YAG laser, synchronizer, PIVCAM, an articulating light arm, control computer, and PIV image capture and analysis software. Both Dantec and TSI performed demonstrations of their systems in the 48-inch water tunnel as part of a down selection process. This system has proven to be exceptional in capturing data covering a large spatial area in a short time frame. What used to take days now takes minutes. Efforts have already begun to develop spatial correlation processing routines for processing of the data. ($122,671)
- A Hewlett Packard 89410A Vector Signal Analyzer was purchased. ($30,402)
- Additional upgrades were made to the traversing and position table for the laser Doppler velocimetry system to allow computer control. ($1,290)
- A Ruska Instrument Corporation 7215xi Pressure Controller was purchased. ($18,797)

A Hewlett Packard 89410A Vector Signal Analyzer was purchased to allow spectral and time domain analysis of signals. This provides two channels of analysis capability from 0 to 10 MHz. It has capabilities for digital demodulation, waterfall and spectrogram, time gated spectral analysis. A signal source is also included.

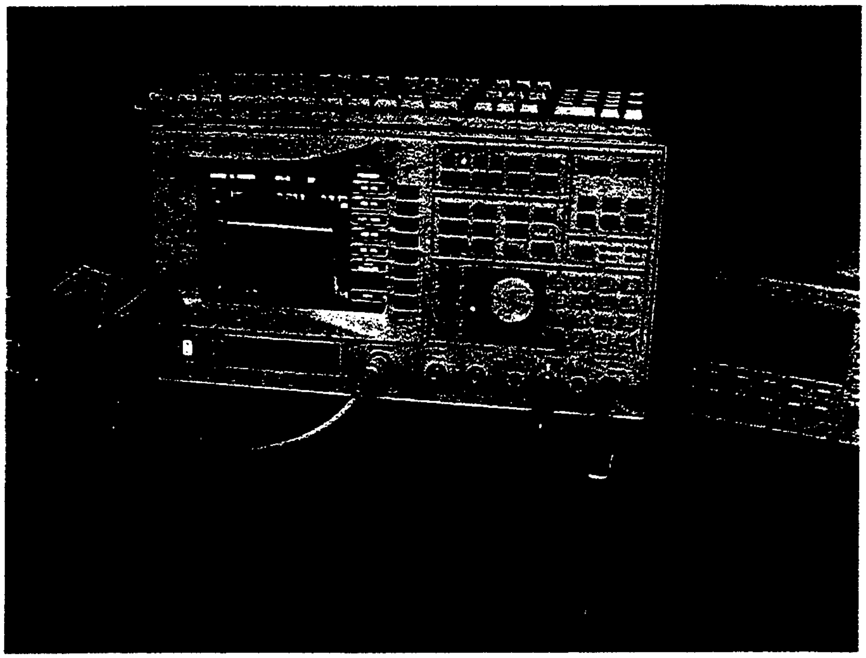


Figure 15. Hewlett Packard 89410A vector signal analyzer.

A Ruska Instrument Corporation 7215xi Pressure Controller was purchased to perform 0 to 100 psi calibrations of all pressure sensor banks for the water tunnel. The unit is supplied with a barometric reference sensor, negative gage mode calibration, and NIST traceable calibration report. Accuracy is 0.011% over the 5-100 psi range and 0.001% of reading for below 5 psi.

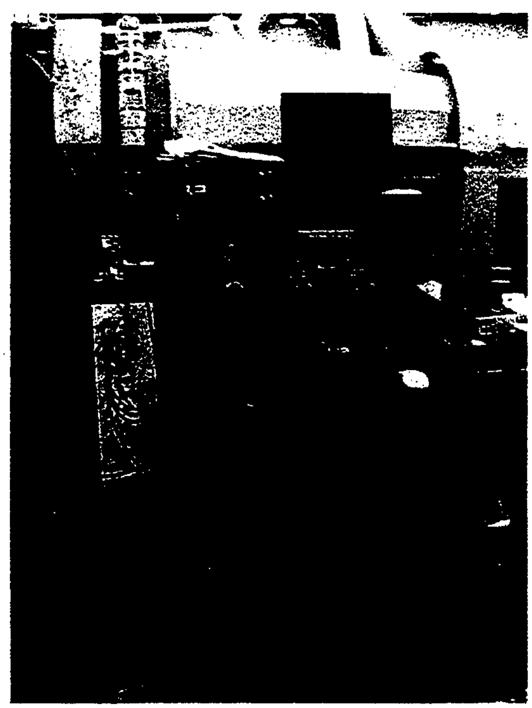


Figure 16. Ruska 7215xi pressure controller for calibration.

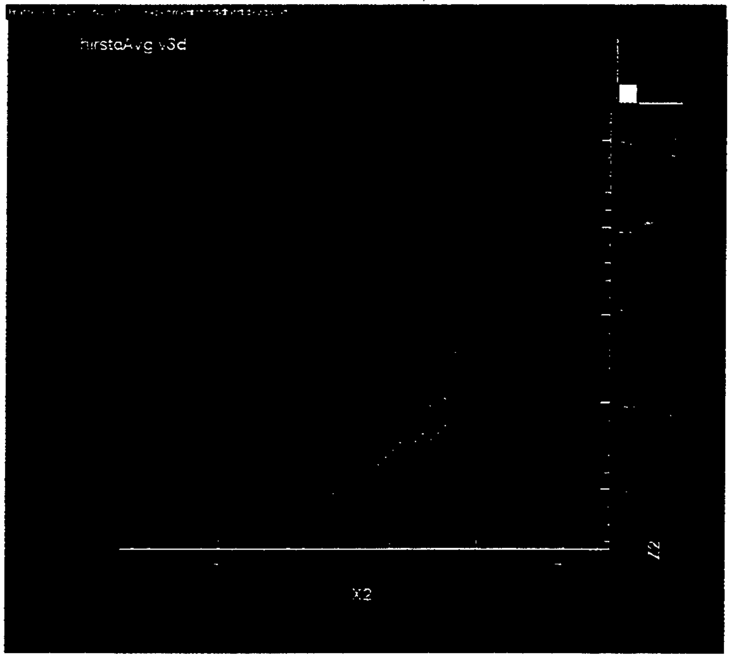
Materials yet to be purchased for the optical data transmission from model subtask are a fiber optic connection tester, CCD microscope, optical test meter, and a fiber optic cleaver. This will be used to develop a capability for signal removal from model mounted sensors without electromagnetic interference.

The major enhancement was the purchase of a stereo particle image velocimetry (PIV) system from TSI, Inc. It includes a mini dual Nd:YAG laser, synchronizer, PIVCAM, an articulating light arm, control computer, and PIV image capture and analysis software. Both Dantec and TSI performed demonstrations of their systems in the 48-inch water tunnel as part of a down selection process.

This system has proven to be exceptional in capturing data covering a large spatial area in a short time frame. What used to take days now takes minutes. Efforts have already begun to develop spatial correlation processing routines for processing of the data. An example of the data obtainable from this PIV system is shown in Figure 17. Examples are given of both an instantaneous capture of the flow field downstream of a rotor and the average flow as determined by several samples. More information on performance is provided in Appendix C.

Figure 17. Averaged and instantaneous PIV images taken downstream of a rotor.

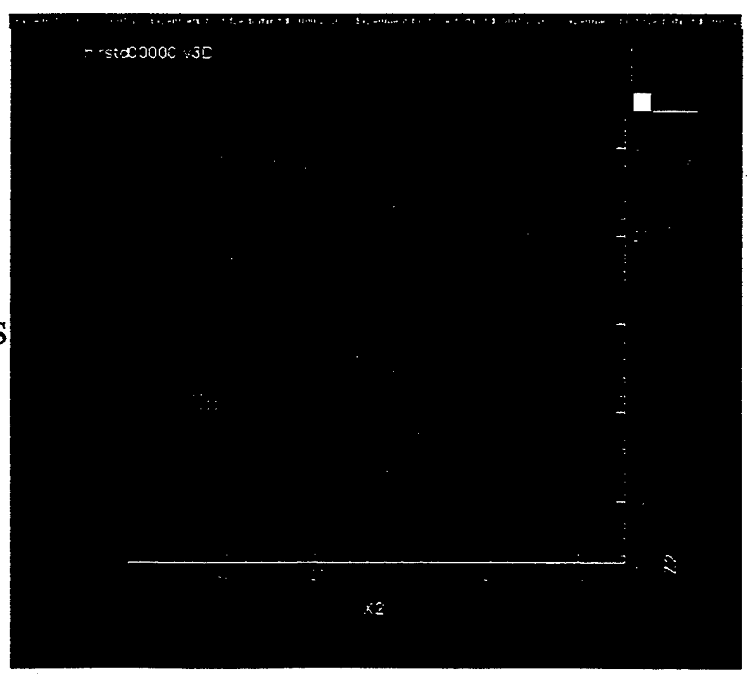
AVERAGED



Axial Flow

Rotor Rotation

INSTANTANEOUS



5.0 Summary

All of the improvements selected have provided significant enhancements to the measurement capabilities for the Garfield Thomas Water Tunnel and the Navy. The PIV system has resulted in more detailed and spatially broader mapping of flow fields and huge savings in test time compared to previous LDV methods. The array and signal processing equipment and the new downstream array have reduced the minimum measurable source levels.

Several additional enhancements to the instrumentation and calibration equipment and acquisition of low noise model motors and drive were part of the option year funding request that was not exercised. They build upon the enhancements made through this project and are still desirable. A listing of these is also provided in Appendix A.

6.0 References

[1] ARL Penn State Letter ser no. FD1747 dated 15 July 1993 with enclosure, ARL Penn State Task Description entitled, " Upgrade of ARL Penn State Hydrodynamic / Hydroacoustic Data Acquisition System," by E. S. Tebay

[2] Marboe, R. C. and Weyer, R. M., "Background Noise Levels in the 48-Inch Water Tunnel After Tunnel Upgrade Program," ARL Penn State Technical Memorandum 88-155, 31 August 1988.

[3] Marboe, R. C., Weyer, R. M. and Welz, J. P., " 48-Inch Water Tunnel Background Noise Reduction," Interoffice Memo, 18 March 1993.

[4] Marboe, R. C., Weyer, R. M., Jonson, M. L., and Thompson, D. E., "Hydroacoustic Research
Capabilities in the Large Water Tunnel at ARL Penn State," *Proceedings of Symposium on Flow Noise Modelling, Measurement, and Control*, NCA-Vol. 15 / FED-Vol. 168, ASME Winter Annual Meeting, New Orleans, LA, 28 November - 3 December 1993, pp. 125-135.

[5] Burroughs, C. B., "Acoustic Measurements in the Large Water Tunnel," Interoffice Memo, 5 May 1993.

[6] Archibald, F. S., Batzel, T. D., Boone, E. F., Masters, R. E., and Welz, J. P., "Position and Status of Tunnel Noise Assessment," Interoffice Memo, 13 October 1998.

[7] NRL/USRD letter Ser no. 5900/045, "ARL Water Tunnel Acoustic Array Design Proposal," 1 September 1994.

[8] Piersol, A. G., "Increasing Signal-to-Noise Ratios of Acoustic Measurements in the Large Water Tunnel," Piersol Engineering Company Technical Memorandum 98-01-01, 28 October 1998.

[9] Allen, C. W., E. C. Myer, and B. L. Kline," Water Tunnel Downstream Array (ARL No. 02-16) Design and Test Report," ARL Penn State Technical Memorandum 02-080, 27 October 2003.

APPENDIX A
PURCHASES PERFORMED UNDER THIS GRANT

The following three pages contain spreadsheets that document the purchases made in each of the four development areas.

The fourth page contains a re-prioritized list of enhancements that would be conducted should the optional $600K funding become available.

	Item		Direct Cost	Qualifies as Capital Equip	Burdened Cost	Req Date	Unburdened Cost
	WATER TUNNEL PHYSICAL PLANT						
	Team Lead - F. E. Smith						
FY01							
	Water Tunnel Ancillary Machinery	**$ 97,063**					
1A	Driveshaft seals		$ 1,068		$ 1,581	2/27/2001	$ 1,067.52
1A	HIREP bearings & seals		$ 3,785		$ 5,606		
	SKF and thrust bearings					3/15/2001	$ 2,419.22
	Bal seals					3/15/2001	$ 1,366.20
1A	HIREP slip ring refurbishment		$ 5,000		$ 7,405		
1A	Piping / Installation for 2nd fill pump		$ 16,102		$ 23,847		
	Changes to quick fill line					2/8/2001	$ 4,813.00
	Core drill and set new fill pump					5/14/2001	$ 4,856.96
	Field changes					7/31/2001	[redacted]
	Electrical parts					8/8/2001	
	connectors, bolts, sealant					8/10/2001	
	wire, bolts	Ivic				8/14/2001	
	600V fuse block	Ivic				8/20/2001	
	starter with solenoid					8/3/2001	
	Install quick fill piping					5/25/2001	$ 4,521.00
	fabricate stainless pipe					5/22/2001	$ 4,965.33
							subtotal
1A	Bay crane overhaul		$ 30,957		$ 45,848	2/7/2001	$ 30,957.32
1A	12 inch WT window frame		$ 5,000		$ 7,405		
1A	Replace city water line valve		$ -		$ -	Complete	$ -
1A	Replace tunnel pressure control		$ 3,626		$ 5,370		
	2 control valves					10/10/2001	[redacted]
	setra sensor	Kline				11/14/2001	
	Replace ceramic heat sink insulators in LWT main						
	DC drive control cabinet	Meyers				1/24/2002	$ 397.86
	Tunnel Windows	**$ 14,205**					
1B	6 side windows		$ 9,572		$ 14,205	3/20/2001	$ 9,572.00
					Paid for by ARL cost center		[redacted]
	ELECTRICAL QUIETING						
	Team Lead - M. L. Jonson						
FY01							
	Electrical Distribution System	**$ 75,075**					
1C	Motor generator for model motors		$ 75,075	$ 75,075	$ 75,075	10/3/2001	$ 74,075.00

	Item			Direct Cost	Qualifies as Capital Equipment	Burdened	Req Date	Unburdened Cost
	ACOUSTIC ARRAY AND ACOUSTIC PROCESSING							
	Team Lead - E. C. Myer							
FY01								
	Replacement Acoustic Array Elements	**$ 111,075**						
2A	Replace elements in downstream array			$ 75,000		$ 111,075		
	1-3 composite						12/7/2001	$ 3,940.00
	Bulkhead connectors						1/9/2002	$ 303.61
	Photo mask for PCB for array		Homan				1/14/2002	$ 140.00
	Photo mask for PCB for array		Homan				1/17/2002	$ 130.00
	Mask for Kaptan shield		Homan				1/23/2002	$ 90.00
	Screws and washers for array mounting		Homan				1/24/2002	$ 33.47
	Cytec Courathane						1/30/2002	$ 199.43
	Metal plate		Meyers				1/21/2002	$ 169.00
	Services???						2/18/2002	$ 35.00
	Purchased service??						2/14/2002	$ 64.73
	Anodizing						2/25/2002	$ 125.00
	Chemlock primer						2/25/2002	$ 101.95
	????						3/15/2002	$ 107.50
	Electronic components		Kline				3/12/2002	$ 672.39
	Electronic components		Kline				3/12/2002	$ 167.35
	Electronic components		Kline				3/12/2002	$ 63.05
	Composite Matls Div Autoclave charges						4/10/2002	$ 335.00
	Hard anodizing						4/17/2002	$ 125.00
	Shipping						3/19/2002	$ 17.54
								subtotal
	Cost Center Charges							
	Systems Engineering							$ 714.42
	Water Tunnel							$ 3,651.20
	Shops							$ 176.74
								Subtotal
	Acoustic Processing System	**$ 107,282**						
2B	LMS Processing System			$ 99,747	$ 99,747	$ 99,747	10/1/2001	$ 99,746.80
2B	Dell Workstation			$ 7,535	$ 7,535	$ 7,535	10/1/2001	$ 7,535.00
	Shipping to Detroit						1/18/2002	$ 89.75
2B	Acoustic Bubble Spectrometer						3/20/2002	$ 21,692.88
	Sensor Calibration Hardware	**$ 49,199**						
3D	Pressure Calibrator			$ 18,797	$ 18,797	$ 18,797	4/16/2001	$ 18,797.56
	High Speed Dynamic Signal Analyzer							
3D	HP 89410A Vector Signal Processor DC to 10 MHz			$ 30,402	$ 30,402	$ 30,402	5/17/2001	$ 30,401.50

	Item		Direct Cost	Qualifies as Capital Equipment	Burdened	Req Date	Unburdened Cost
	ADVANCED OPTICAL INSTRUMENTATION						
	Team Lead - A. A. Fontaine						
FY01							
	PIV and LDV Systems						
3A	Particle Image Velocimetry System	**$ 122,669**					
	Stereo PIV system from TSI		$ 120,935	$ 120,935	$ 120,935	4/17/2001	$120,935.00
	1 GB RAM upgrade		$ 932	$ -	$ 1,380	9/20/2001	$ 932.00
	73 GB disk drive		$ 239	$ -	$ 354	9/20/2001	$ 239.00
3A	Laser Doppler Velocimetry System Upgrade	**$ 1,290**					
	Traversing Table upgrades		$ 871		$ 1,290		
	Bracing material					2/12/2001	$ 68.88
	Socket head screws					2/13/2001	$ 23.37
	Cable					2/28/2001	$ 250.00
	Motor rack					3/5/2001	$ 339.82
	Anodizing					3/12/2001	$ 38.79
	Anodizing					3/14/2001	$ 140.00
	ML Shop cost center					3/28/2001	$ 10.00

Second $600K

	Item		Direct Cost	Qualifies as Capital Equipment	Burdened
	WATER TUNNEL PHYSICAL PLANT				
	Water Tunnel Ancillary Machinery	**$ 112,256**			
1A	Install new fill/drain line with pump between 30K and 60K storage tanks		$ 18,000		$ 26,658
1A	HIREP slip ring replacement		$ 30,000	$ 30,000	$ 30,000
1A	Replace acoustic window in hatch tank		$ 20,000		$ 29,680
1A	Components for calibration tunnel		$ 17,500		$ 25,918
	Low Noise Model Motors	**$ 80,000**			
1C	Low noise slotless model motors		$ 40,000	$ 40,000	$ 40,000
1D	New inverter with filter		$ 40,000	$ 40,000	$ 40,000
	ACOUSTIC ARRAY AND ACOUSTIC PROCESSING				
	Noise and Vibration Monitoring System	**$ 77,000**			
2C	Odyssey upgrade of 4 ch 500kHz		$ 27,000	$ 27,000	$ 27,000
2C	Filter/amplifiers - 16 chan		$ 50,000	$ 50,000	$ 50,000
	ADVANCED INSTRUMENTATION, DATA ACQUISITION, AND CALIBRATION EQUIPMENT				
3A	Particle Image Velocimetry System	**$ 40,367**			
	PIV four-processor workstation		$ 7,000		$ 10,367
	High-resolution, in-body PIV camera		$ 30,000	$ 30,000	$ 30,000
3A	Laser Doppler Velocimetry System Upgrade	**$ 99,457**			
	LDV IFA processor upgrade		$ 56,900	$ 56,900	$ 56,900
	LDV rotating machinery resolver		$ 4,900		$ 7,257
	LDV three-channel photodector		$ 15,300	$ 15,300	$ 15,300
	Coherent I90 laser		$ 20,000	$ 20,000	$ 20,000
	Optical Data Path	**$ 52,620**			
3B	Optical Data Transmission from Models		$ 43,000	$ 23,000	$ 52,620
	optical signal analyzer				
	fiber optic connection tester				
	CCD microscope				
	optical test meter				
	fiber optic cleaver				
	Data Acquisition Hardware/Software	**$ 41,275**			
3C	Data Storage		$ 15,000	$ 15,000	$ 15,000
3C	LMS expansion chassis and 8 data acquisition channels		$ 16,500	$ 16,500	$ 16,500
3C	Relay Mux replacement (2)		$ 1,600		$ 2,370
3C	Ethernet-based stepper motor controller (2)		$ 5,000		$ 7,405
	Sensor Calibration Hardware	**$ 46,342**			
3D	SigLab MC50-42 (calibration)		$ 14,050	$ 14,050	$ 14,050
3D	Dynamic in-tunnel balancing system		$ 20,000	$ 20,000	$ 20,000
3D	Random noise generators (2)		$ 5,000		$ 7,405
3D	F3 Shaker, with impedance head		$ 3,300		$ 4,887
		$ 549,316	$ 500,050	$ 397,750	$ 549,256
	Target Hardware/Software	**$ 550,000**			
	Manpower	**$ 50,000**			
	TOTAL	**$ 600,000**			

APPENDIX B
MOTOR-GENERATOR SET IMPACT STUDY

B.1 Introduction

The Garfield Thomas Water Tunnel has a firmly established tradition of leadership in the field of submarine, surface ship, and torpedo propulsor development. Among the most historically significant measurement capabilities in the area of hydroacoustics is the unsteady propulsor force measurement. Unsteady forces are generated by the interaction of the propulsor with its spatially non-uniform inflow. As with any kind of acoustic measurement, while propulsor design has improved from generation to generation, the amplitude of unsteady forces have decreased toward the threshold of detection. The successful suppression of propulsor generated unsteady force levels has resulted in constantly decreasing signal-to-noise ratio levels in the measurement system. Over recent years, several improvements have been made in the area of instrument sensitivity improvement. These efforts have reclaimed some of the signal-to-noise ratio levels which have been lost through design improvement through the years.

Currently, propulsor generated unsteady force levels are approaching the levels of forces generated in the model motors. These forces are generated as a result of drive current waveform distortion, stator-pole interaction and the structural response of motor components to the fluctuating magnetic field generated in the stator. These motor generated forces, and the response of the mechanical assembly, contaminate the measurement system and represent the current noise floor in shaft unsteady force measurements. The dominant cause of motor vibration at frequencies that affect measurements is drive current waveform distortion. The model motors in the water tunnel are powered through a six-step inverter which produces a current waveform that is a very crude approximation of a sinusoid, as shown in figure B-1. Fourier decomposition of the six-step waveform reveals a significant amount on energy distributed into harmonics of the desired drive frequency. These harmonics don't produce a net torque between the rotor and the stator. Instead, the harmonics induce vibrations in the motor stator, cause angular acceleration harmonics in the motor rotor (torque ripple), and are dissipated as heat.

One method for eliminating the motor drive harmonics is to insert an intermediate motor/generator (MG) set between the inverter and the drive motor. This configuration mechanically isolates the drive motors from the unsteady forces generated by the distorted drive waveform supplied by the inverter. The waveform supplied by the generator to the drive motor is relatively free from these drive current harmonics. This appendix presents an assessment of the impact of an MG set on water tunnel operations including considerations of unsteady force measurement and powering measurements.

B.2 Experimental Observations

A series of experiments were performed in order to quantify the potential performance improvement provided by a more sinusoidal motor drive current. A 56kW (75 HP) motor was evaluated during operation with a six-step inverter and also with the intermediate MG set isolating the motor from the six-step inverter. Measurements included drive current spectra, motor vibration spectra and radiating magnetic field spectra. Motor drive current measurements were made on a single motor lead with a clip-on ammeter. Motor vibration was measured with a single radial accelerometer mounted on the motor casing. Radiating field measurements were made with a coil-type field sensor. Data were acquired at various motor drive speeds under no-load conditions. Characteristic differences between drive configurations existed for all drive speeds.

A comparison of the drive configurations is presented in figure B-2. The upper plot illustrates the potential reduction in motor vibration spectrum through installation of an MG set between the six-step inverter and the drive motors. The blue curve represents the vibration spectrum associated with driving the motor directly from the inverter. The red curve represents the vibration spectrum resulting from installation of the MG set between the inverter and the drive motor. Black diamonds are placed on the spectra at frequencies where drive current harmonics occur; i.e. 24, 48, 72 and 96 times the mechanical frequency or shaft rotation rate. This data set indicates that radial vibration levels are reduced by more than 20 dB at the first three harmonics of the drive frequency through the use of an MG set. A comparison of the measurements of the drive current harmonics between the inverter and the MG set is provided in the lower plot in figure B-2. This data indicate that a nominal 50 dB reduction in drive current harmonics occurs through the use of the MG set. At the second harmonic of drive current, the reduction is around 20 dB because there is also a stator-pole interaction at this frequency. The observations of the spectral characteristics of noise in unsteady shaft force measurements suggest that the source of excitation is more closely related to the drive current harmonics than the motor vibration harmonics. The implied conclusion is that the use of an MG set for model motor powering should improve signal-to-noise ratio levels by between 20 and 50 dB at the harmonics of drive current. Clearly in the absence of a serious adverse effect, the decision to implement M/G set drive for model motors is justifiable.

B.3 Results of Modeling

In order to ensure that no loss in powering capability would result from installation of an M/G set, a model of M/G set coupled to a generic drive motor was developed. The M/G set's principal output parameters are drive frequency, output voltage and available current. The quoted M/G set has an output voltage characteristic that varies linearly with drive frequency as shown in the upper inset in figure B-3. At a drive frequency of 150Hz, the output voltage is clamped at 600 volts. Considering the M/G set current limit of 350Amps, the maximum M/G set output power peaks at 440hp. For an ideal motor, the relationship between torque and power is assumed to be linear. This assumption transforms the rising power segment of the M/G set output characteristic curve into a constant torque model motor characteristic. At frequencies above 150Hz, the model motor power would be constant because the M/G set output power is constant. The lower inset in figure B-3 indicates how the maximum available model motor torque and the cross-over frequency vary with respect to the number of poles in the model motor. The cross-over frequency is simply the mechanical frequency that corresponds to the electrical frequency of 150Hz. It is calculated by dividing the electrical frequency by the number of pole pairs. The maximum available model motor torque is calculated based upon the assumption of conservation of power. Motors with lower pole numbers run at higher speeds but have lower values of maximum available torque. Frequently, in water tunnel applications, propulsor powering characteristics significantly tax the ability of the drive system to provide torque at low operating speeds. Figure B-3 illustrates the torque-speed availability curves for an idealized motor of varying pole number. In each case, the motor is assumed to be capable of converting the maximum output power of the M/G set into useful work with a 90% thermal efficiency. Each of these curves exhibits a constant torque regime where the maximum available torque is highly dependent upon the number of motor poles. The curves also exhibit a constant power portion. The assumption of 90% thermal efficiency places this constant power curve at 440 hp. In order to assess the impact of M/G set installation on water tunnel model powering capabilities, this set of idealized motor performance curves must be compared to existing water tunnel model motors. The most frequently used dynamometer configuration includes two 75 hp induction motors that together deliver a maximum of 350 ft-lbf of torque throughout a speed range up to 2250 rpm. At this point the torque-speed curve follows a curve of constant power i.e. 150 hp. It is clear from figure B-3 that the torque limit attributable to the Motor/Generator set would not be the limiting factor in determining the low-speed torque available for model powering.

The restriction in available torque is mostly due to the fact that the 75 hp motors are limited to drive currents of 100 amps per phase while the M/G set is capable of delivering 350 amps per phase. If the dynamometer were redesigned to accommodate new motors that would be capable of handling 350 amps, a 650 ft-lb_f torque limit would result, providing the new motors had the same torque-current behavior as the existing motors. If the new motors had the same volume specific torque capability as the existing motors, an increase in dynamometer volume of 75% would be required.

Enhancements in the model motor torque limit might be realized through a variety of methods without the need for significant dynamometer redesign. The 100 amp per phase current limit on the existing motors is based upon material temperature limits within the motor stator. For these motors, the duty rating disallows operation at higher currents in order to prevent internal motor damage. These motors must be operated with a conservative duty rating because there is no internal temperature monitoring system to allow underway assessment of the thermal condition of the motor. A more aggressive duty rating could be applied if a motor internal thermal monitoring system and a robust temperature control system were available. Isolated retrofit of a thermal monitoring system is unlikely to be justifiable. Installing this capability when motors are being rewound is a more attractive scenario. It is conceivable that a retrofit thermal monitor along with a more robust cooling system would provide an additional 15% of model motor torque.

This suggested motor modification strategy does not increase the efficiency of the motor but instead simply provides a more effective means of removing the dissipated heat from the motor. There are a variety of opportunities to increase the volume specific torque availability by decreasing the fraction of energy that is dissipated as heat. The M/G set drive itself may, in fact, enhance the effective motor thermal efficiency. The six-step current waveform presently used to power model motors distributes approximately 20% of the drive energy into higher harmonics of the fundamental electrical frequency. This energy produces no shaft power but instead is dissipated as heat. With the sinusoidal drive current delivered by the M/G set, no higher harmonic energy is dissipated as heat in the motor stator windings. This effective thermal efficiency increase can only be realized, however, by reevaluation of the motor duty rating.

B.4 Conclusions and Recommendations

In summary, installation of an M/G set for model motor drive in the water tunnel has a number of advantages without any notable drawbacks.

- The signal-to-noise ratio for low-frequency unsteady force measurements will be improved by between 20 and 50 dB.
- Powering capability is not sacrificed to obtain the acoustics benefit.
- M/G set powering capabilities significantly exceed present model motor power conversion capabilities.
- Use of the M/G set in place of an inverter should provide a significant increment of effective thermal efficiency in the drive motors which might be secured to enhance the low speed torque operational capabilities of existing drive motors.

B.5 Motor-Generator Set Specifications

After consideration of the conclusions reviewed above, a motor-generator set was purchased with the following specifications.

Vendor:

Associated Electric
171 West Main Street
Hillsboro NH 03244
800-746-5900

General Information:

Drive motor connected for 240 Vac, 3-phase input @ 60 Hz max input 480 amps. Range of operation 10 Hz –180 Hz input @ 4 V/Hz; max speed of 3600 rpm.

Alternator connected for 240 Vac, 3-phase output @ 60 Hz max output 350 amp max output voltage 600 Vac @ 150 & 180 Hz.

230 Vac, 3-phase control power supply is required @ 50-70 amps.

Alternator output is controlled by adjusting variable voltage transformer. Minimum excitation input no-load is 12 Vdc @ 12 amps. Adjust as required to maintain A/C output voltages load increases or decreases.

At 200 rpm contactors for excitation and cooling blowers will energize, and will de-energize below 200 rpm.

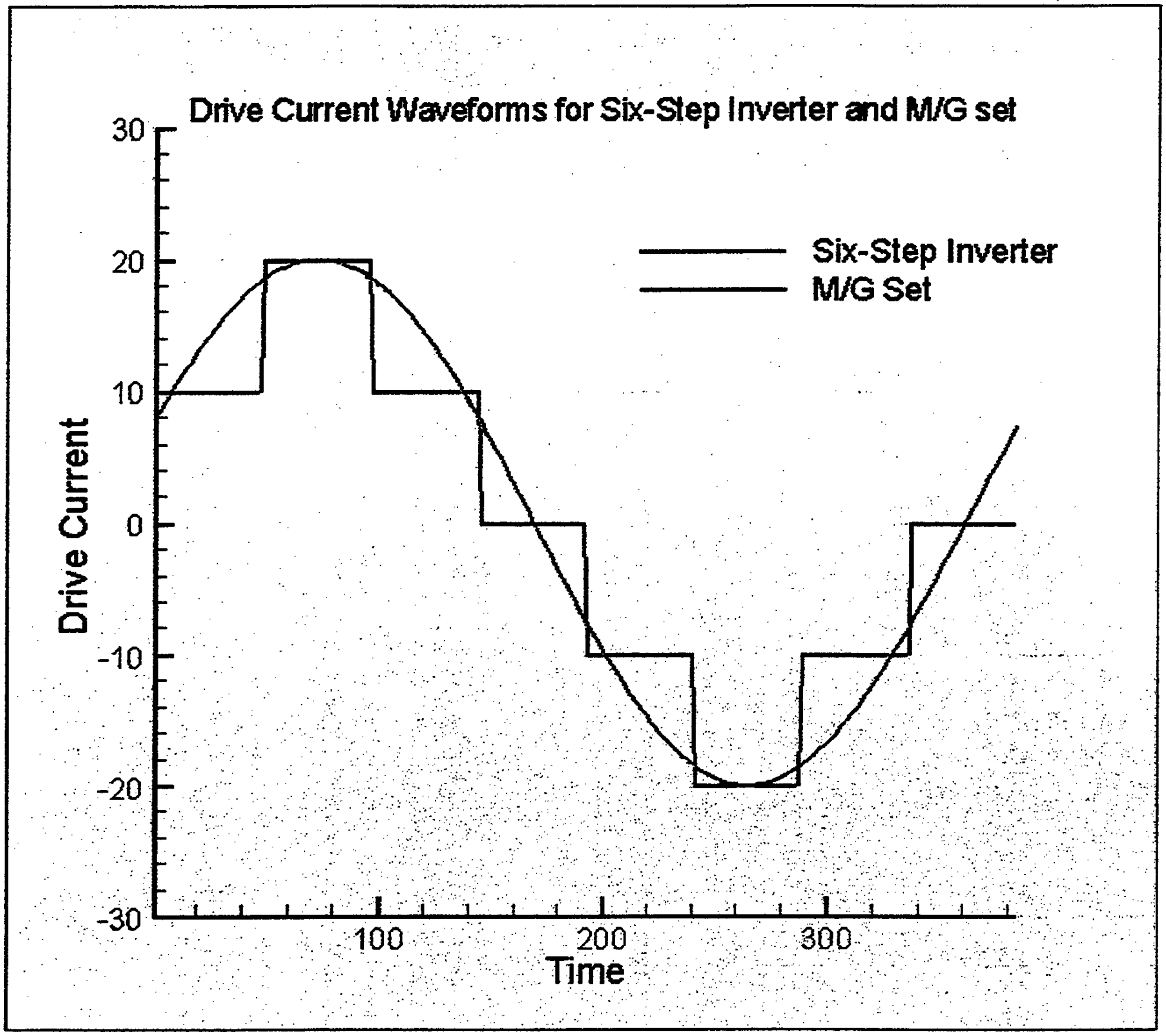


Figure B-1. Representation of various current waveforms.

Pump Loop Motor Drive System Evaluation - 900 RPM

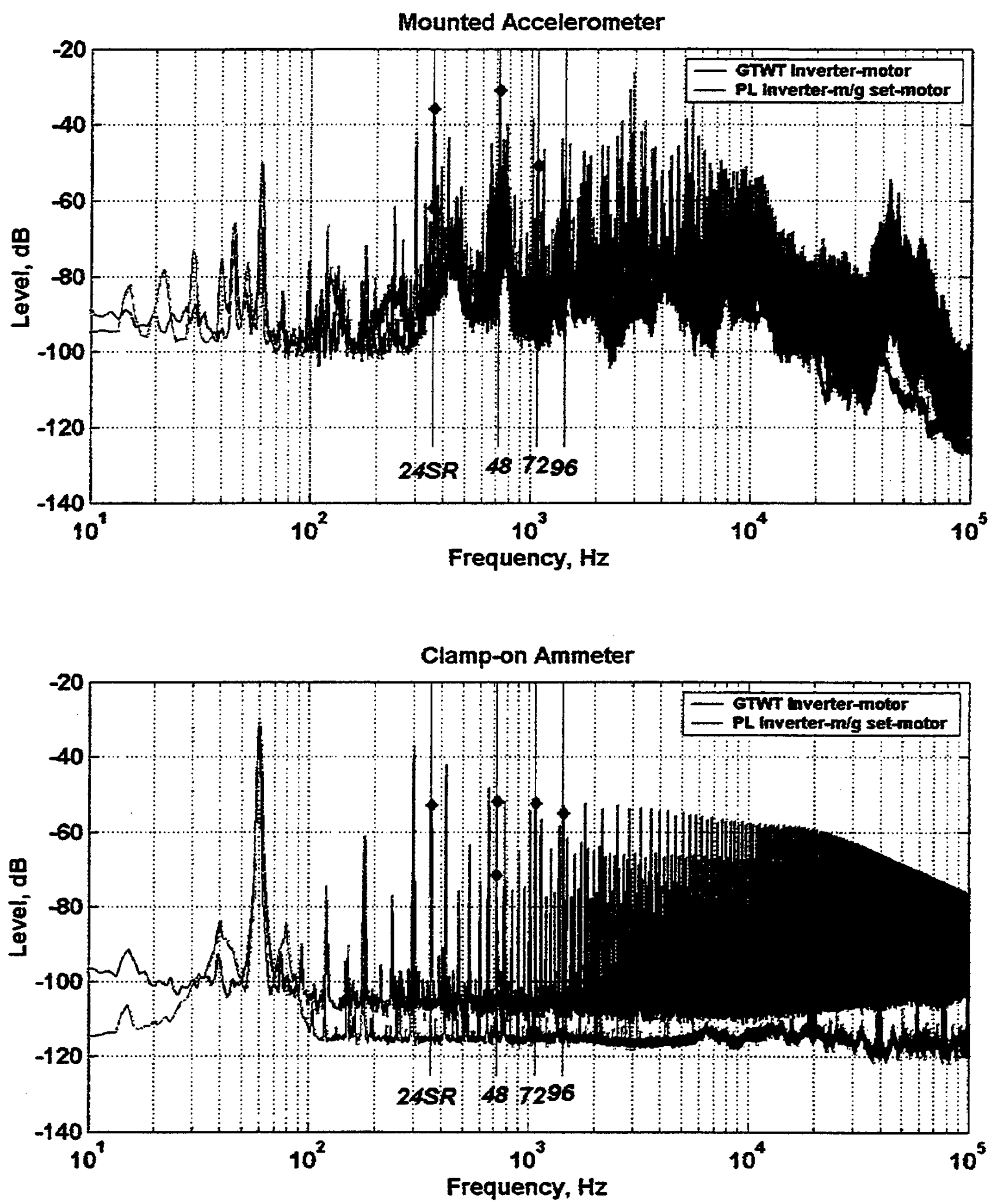


Figure B-2. Measured responses associated with various drive waveforms.

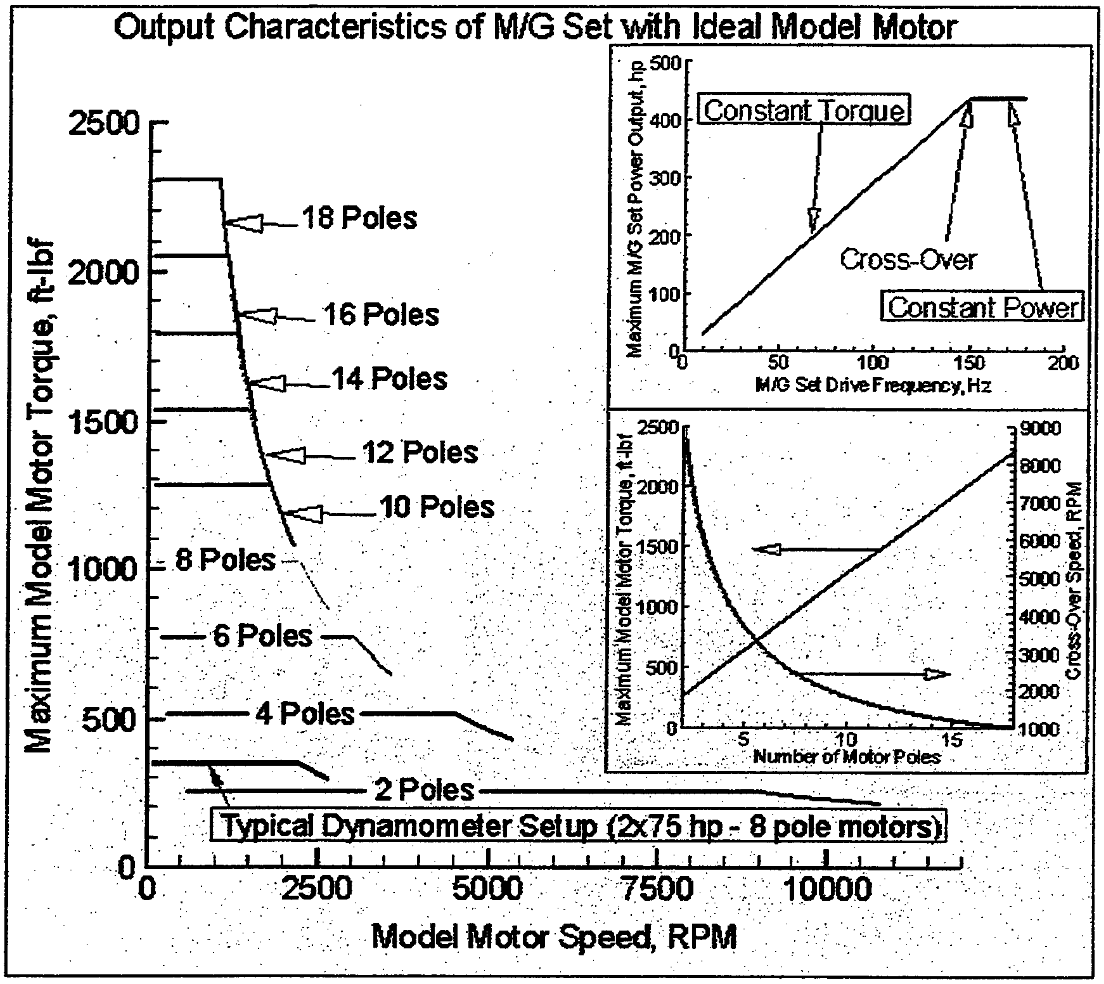


Figure B-3. Model powering characteristics related to various drive configurations.

APPENDIX C
DESCRIPTION OF THE PARTICLE IMAGE VELOCIMETRY SYSTEM

The ONR water tunnel upgrade project included funds for the acquisition of a state-of-the-art digital particle image velocimetry (DPIV) system for advanced flow field measurements. Commercial DPIV systems are now advanced to the stage that 48" tunnel measurements, using these systems, are now practical, cost efficient, and desirable for complex flow field measurements. This appendix documents the procedure followed in the selection and acquisition process of a DPIV system for the water tunnel.

After internal review of a comparison between commercially available systems, and the time and cost to develop a unique in-house system, it was determined that commercial systems exist that would satisfy water tunnel requirements and system specifications. The required system specifications for a DPIV system at the water tunnel are listed as follows.

1. The system must be a stand alone, planar system with straightforward 3-D stereoscopic capability or with the ability to expand to 3-D capabilities at a later time.
2. The system must be compatible with existing water tunnel hardware and software for image acquisition and processing, traverse control and analog signal input and analysis.
3. The system must have high speed real time processing, and the capability for off-line batch processing.
4. The system must have enhanced resolution through both hardware and data processing methodologies.
5. System calibration must be available using rigid calibration targets that can be mounted to water tunnel models and that can be immersed. The calibration target used for stereoscopic imaging must be a dual plane target that does not require manual displacement of the target.
6. The system must use dual pulsed Yag lasers with a minimum 100 mJ/pulse of energy in the green wavelength.
7. The system must be able to govern laser energy through manual and software controls.
8. A variety of interchangeable light sheet optics must be available to produce thin (less than 1 mm) light sheets capable of illuminating a field of view ranging from 0.5" by 0.5" to over 10" by 10".
9. A remote, Yag laser light transmission system must be available to project the light sheet from locations up to 6 feet from the laser output aperture.

The best commercial systems were identified that met or exceeded the above system specifications, and were invited to compete for a sale by participating in a 48" tunnel demonstration on an experiment defined by ARL. The competition involved having each vendor bring their system under consideration and use it to acquire data in the defined 48" tunnel experiment setup and run by ARL personnel. This method of competition provides a fair assessment of each system as each vendor has the opportunity to demonstrate their system on identical experiments with their trained personnel. The experiment was set up to provide a test for variability in field of view, light sheet capabilities, spatial resolution, image quality, calibration technique, seeding requirements and accuracy of the processed data when compared to laser Doppler velocimetry data at the same locations in the same experiment.

The experiment, set up for the demonstrations, involved a jet exiting out of a 4" nozzle into a co-flowing stream. The nozzle was inclined at approximately a 10 degree angle to the co-flowing stream, and was positioned roughly 5" above a flat plate model generating a thick turbulent boundary layer. The experimental facility is illustrated in Figure C-1. The ratio of the jet exit velocity to the co-flow axial velocity was roughly 1.5, and the incoming turbulent boundary layer had a thickness of approximately 2 inches. Prior to demonstrating the DPIV systems, laser Doppler velocimetry measurements were made to quantify the jet exit velocity field and the turbulent boundary layer growing on the plate. As a part of the demonstration and evaluation process, the DPIV data were compared to the LDV data for accuracy and spatial resolution.

Based on the outcome of the demonstrations, a TSI Ultra Stereoscopic DPIV system was purchased. This is a standard TSI system with minor modifications for use at the water tunnel. The water tunnel system uses two Cooke Corp. (PCO) Sensicam cameras with 1k by 1.25k pixel resolution. These are high quality, laboratory grade CCD cameras with high-resolution square pixel chips. The Sensicam cameras have very low light level sensitivity, ideal for water tunnel use. The system uses a 1GHz Dell PC with 1 Gig of RAM and 100 GByte HDD. The computer has a 12x cd-rw CD writer and a dual sided DVD writer (capable of burning > 9GBytes on a disk) for data backup. The system is compatible with the various traverse systems available at the tunnel, and the system software is capable of controlling these systems. A New Wave Gemini PIV-120 YAG laser is used to generate the laser light for the light sheet optics. This is a compact dual-cavity ND:Yag pulsed laser. The two laser heads are powered by separate power supplies and are controlled individually. The intensity of the output beam is controlled manually on the laser power supplies or via software control of the q-switches. A two meter light sheet arm was purchased to provide remote positioning of the light sheet optics relative to the laser head. This capability allows us to position and control the position of the light sheet optics

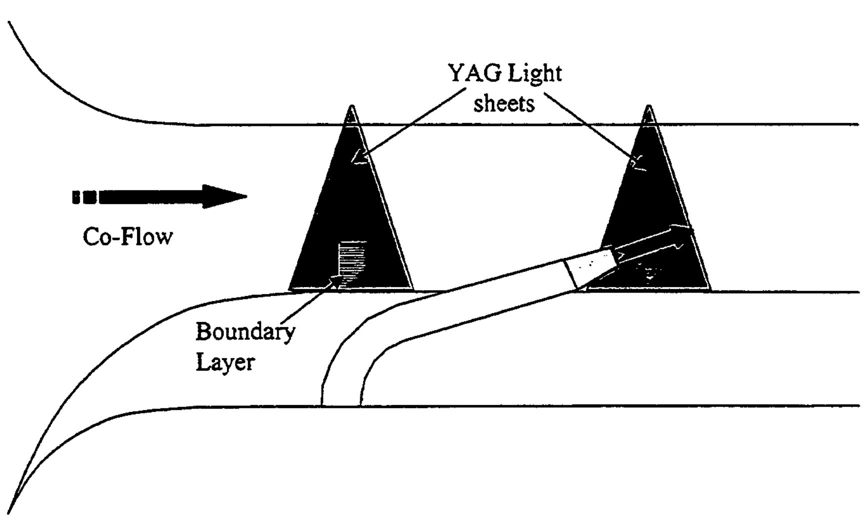


Figure C-1. Schematic of the demo experiment setup.

within any laser window of the tunnel. The DPIV system can be synchronized to water tunnel encoders for encoded imaging on rotating machinery. The water tunnel system also has analog signal sampling permitting digitizing of up to 32 channels of analog signals simultaneously with each image. This gives the water tunnel the ability to perform instantaneous measurements of fluid/structure interactions.

The system was delivered in late April and was operational by early June of 2001. Since June of 2001, the system has been used successfully on several 48-inch water tunnel projects and several 12" water tunnel projects. In several of these tests, the DPIV system was compared to LDV measured data to assess system performance and accuracy of the data. The following list summarizes several of different types of tests that the system has been used on.

48" Tunnel:

1. Large Gap HIREP Test : DPIV data were acquired in the wake of an upstream inlet strut, and in the flow field downstream of a rotor blade near the tip region. Planar, 2-D data were acquired in the wake of the inlet strut, while a combination of 2-D and stereoscopic 3-D data were acquired downstream of the rotor tips. The measurements conducted downstream of the rotor blades were acquired in both a non-encoded and encoded mode to provide long time average vector fields and phase window averaged vector fields of the exit flow field, respectively. The upstream DPIV results showed excellent agreement with LDV measured data of the turbulent wake profiles exiting the strut. In addition, these instantaneous planar vector maps provide insight into the actual wake size and dynamics shed from the upstream strut, data unavailable with LDV. Figure C-2 shows a sample vector map obtained in the wake of the upstream strut.
2. Water Jet: DPIV measurements were obtained in the exit jet flow field of an approximate 1/20 scale model of a water jet propulsor. The DPIV measurements were conducted in the exit jet and used to map the jet exit velocity field over a range of powering conditions. These data were compared to limited LDV measured data of the jet exit flow field for limited operating conditions.
3. Podded Propulsor Flow Field Evaluation: During this test, the DPIV system was used to map the inlet and outlet flow field of candidate propellers used in podded propulsion systems on surface ships. Limited measurements were compared with LDV. The DPIV system saved roughly an order of magnitude in time if the same data set had been taken with LDV. In addition, the DPIV data can be used to compute actual length scale estimates of the turbulent flow field ingested into the propeller, a non-trivial and very time consuming task for LDV.

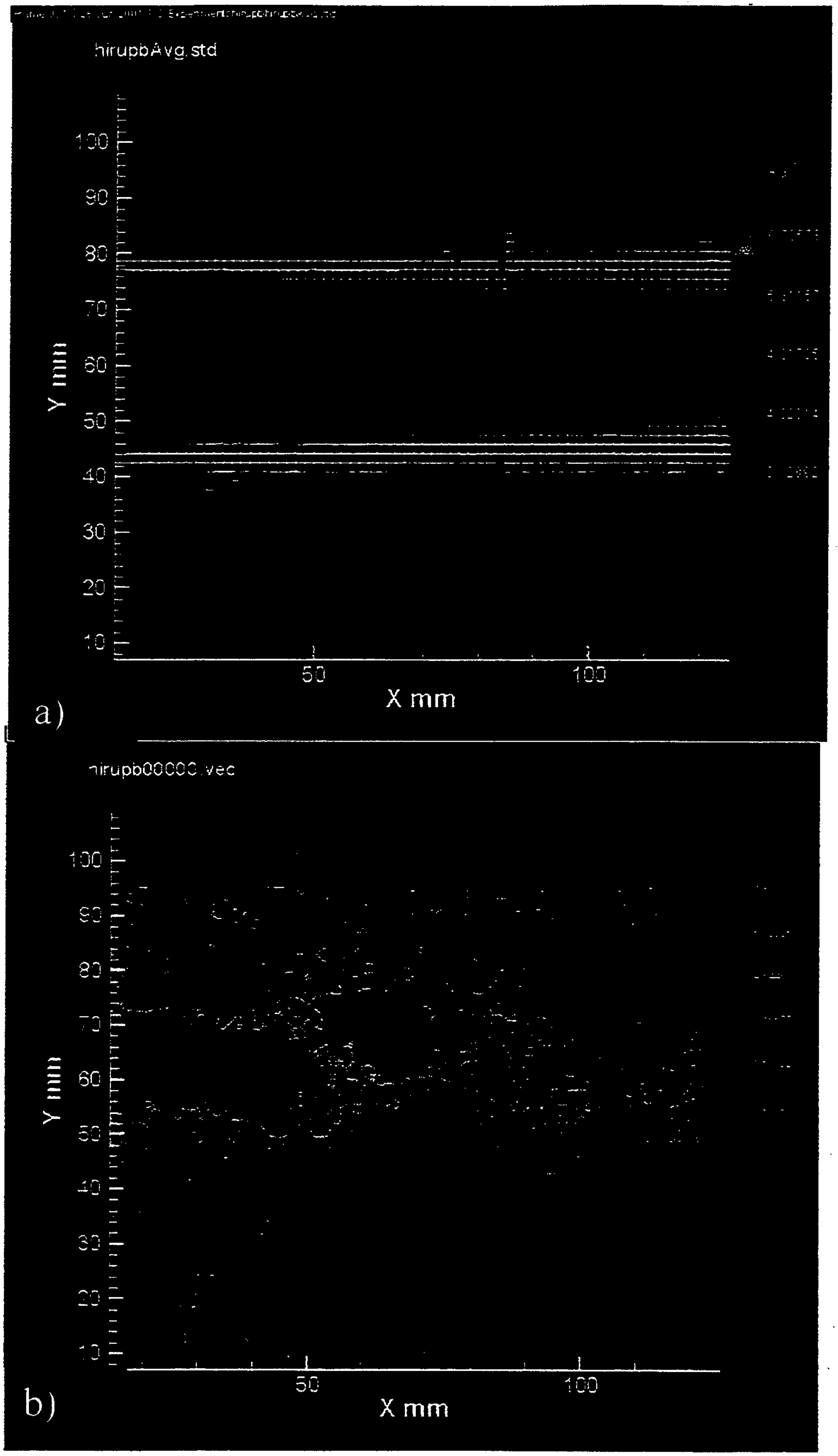


Figure C-2. DPIV vector maps of the wake flow shed from an upstream strut. a) Mean axial vector map. b) Instantaneous axial contour map.

12" Tunnel:

1. Cylindrical Micro-bubble Drag Reduction: Turbulent boundary layer profiles were measured on the 3.5" diameter cylindrical microbubble body to characterize the boundary layer along the length of the body. The DPIV system provided an accurate and quick measure of the boundary layer profiles in a fraction of the time it would have taken if performed by LDV. A limited set of the DPIV profile data was compared with LDV measured profiles to assess data uncertainty. Figure C-3 shows an instanteneous contour map of the measured turbulent boundary layer on the microbubble body.
2. Synergistic Drag Reduction: The DPIV system was used to measure the turbulent boundary layer characteristics, including Reynolds stresses, in the rectangular test section with and without polymer additives.

The water tunnel DPIV system will be put through a system qualification in the next calendar year. The system qualification procedure will involve, a determination of the system accuracy, noise sources in the measurement system, an assessment of the dynamic range of the system and

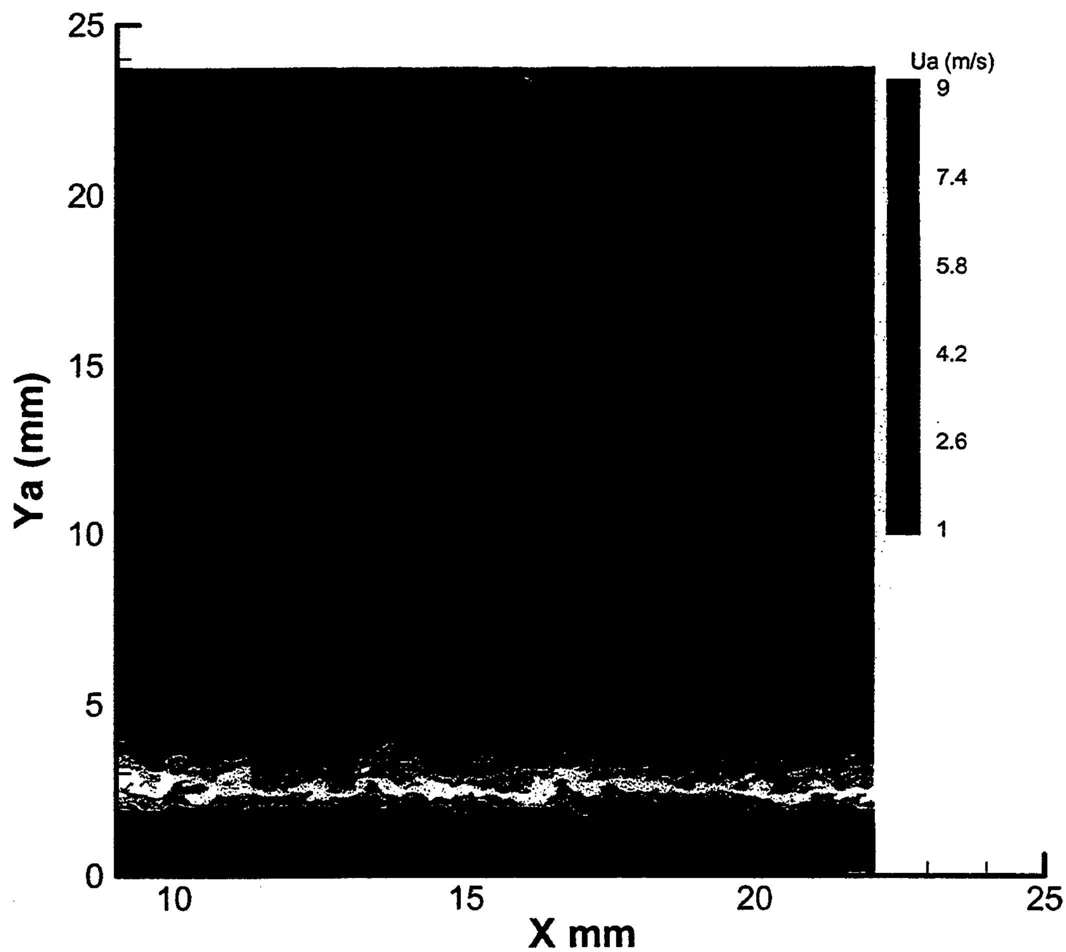


Figure C-3. DPIV measured color contour map of the turbulent boundary layer on the cylindrical microbubble body.

the resolution capabilities for both the 2-D planar setup and 3-D stereoscopic setup. In addition, the stereoscopic setup will also be evaluated for accuracy of the out of plane component and the sensitivity of this accuracy to calibration procedure. A series of tests conducted in three of the water tunnel facilities will be performed to accomplish this system qualification.

Planar DPIV measurements will be made in the glycerin tunnel test section to assess the accuracy of the system, and to identify noise sources or noise floors in the system. The glycerin tunnel will be run in both the turbulent and laminar flow regimes. In the turbulent flow regime, the tunnel is well characterized using hot film anemometry and LDV. The accuracy of the DPIV system to measure mean and Reynolds stresses can be assessed by comparison with the documented flow field of the tunnel. Statistical convergence tests will be performed to identify the minimum number images required to calculate velocity statistics up to second order within a specified level of uncertainty. Spatial resolution tests will be conducted to assess optical limitations in achieving high spatial resolution. Since the flow field is essentially a fully developed turbulent pipe flow, there is no non-axial mean velocity component, and the turbulent length scales are well documented. This flow field allows us to assess any bias in measuring zero mean velocity, and allows us to identify the uncertainties in estimating turbulent length scales from DPIV data. By running the tunnel in the laminar flow mode, we can assess the noise floor in measuring turbulence quantities such as rms velocities and Reynolds stresses. In the laminar flow mode, the tunnel has low rms levels in the axial and radial components as documented by LDV and hot film anemometry. DPIV data are acquired and the statistics calculated from the ensemble vector maps. The DPIV measured rms levels and how these levels vary with the number of ensembles provides a rough estimate of the noise levels in the system. This procedure has been successfully used to assess noise floors in the water tunnel's LDV systems.

The 12" and 48" water tunnels continue to be used to assess the quality of both the planar and stereoscopic systems. DPIV measurements have been obtained in the freestream flow field of both tunnels. These measurements provided data for an assessment of the bias errors and noise floors of the DPIV system at higher Reynolds numbers than in the Glycerin. The higher Reynolds numbers and smaller spatial scales of the water tunnel environment impose greater constraints on seeding requirements than in the glycerin tunnel, and place higher demands on spatial resolution. Imaging has been performed over greater focal distances and over a wider range of field of view. The sensitivity of the uncertainty of the computed velocities to the accuracy of the calibration procedure continues to be assessed for both planar and stereoscopic DPIV. The uniform freestream flow field provides an excellent test case to assess the errors in measuring the perpendicular, third component of velocity with the stereoscopic DPIV system. This third component of velocity has a zero mean in the central section of the water tunnel test section, and provides a good test case for assessing the how well the DPIV system resolves this low velocity component.

In summary, the major improvements resulting from the addition of a DPIV measurement system to the GTWT suite of measurement capabilities are as follows.

- Up to an order of magnitude reduction in the amount of time to acquire a specified set of velocity data (flow field mapping in 2-D & 3-D space) using DPIV compared to LDV, hot-film or pressure type probes. This reduction in time has a significant impact on the efficiency and cost to perform a test. Furthermore, the use of DPIV (when applicable) provides flexibility in defining the amount of data to be acquired, for example, more data can be measured at additional locations or test conditions for a fixed amount of test time. It takes the guess work out of having to predetermine where a particular flow feature of interest may be spatially, thus saving test time.

- DPIV data is ideally suited for multi-point turbulence measurements. The planar vector maps permit easy calculation of the two-point, spatial velocity correlations, and thus, provide a direct measure of the turbulent length scales in the flow. These length scales are important input parameters for current hydro-acoustic noise prediction tools, and are typically estimated by indirect methods often relying on questionable assumptions about the flow field under study. ARL has developed the necessary post-processing capabilities to compute the two-point, spatial velocity correlations and length scales from DPIV measured velocity fields.

- While LDV has the capability of a higher frequency response then DPIV, LDV provides only an instantaneous value of a local fluctuating velocity at a point. DPIV provides an instantaneous snapshot of a 2-D planar flow field at many points in the field of view. This has the advantage of delivering more detailed information on the dynamics of unsteady localized flow structures such as wakes shed from upstream appendages and vortices impacting flow field boundaries. The data represented in Figure C-2 above is a perfect example of the advantageous of DPIV measurements over LDV in some cases. The time-averaged wake illustrated in Figure C-2a shows the typical wake type profile. This vector map showed excellent agreement with wake profiles measured at several axial locations using LDV. The acquisition time for the DPIV measured data was roughly an order of magnitude less than the limited LDV data, and provides more detail of the wake development downstream. In addition, the instantaneous vector maps, illustrated in Figure C-2b, show a narrower wake structure that exhibits a cross-stream meandering due to the Strouhal shedding of the wake from the upstream strut. The long time averaging of this unsteady wandering of the wake has the effect of smoothing out the wake details and artificially increasing the width of the wake when compared to the instantaneous vector field. This averaging would also have the effect of increasing the calculated turbulent length scales in the wake when compared to the instantaneous values.

- Coupled with the advanced data acquisition capabilities purchased with the DPIV system and in-house at the GTWT, the DPIV system can be used to study flow / structure interactions. Measurements can be performed to investigate the impact of unsteady flow structures on downstream appendages, and the resulting time-dependant vibration and pressure signals generated in and on the surface of the appendage. Instantaneous vector maps of unsteady wakes impacting a structure can be acquired and synchronized to digitized signals from accelerometers and pressure sensors acquired pre and post impact of the wake. This capability allows us to directly measure the correlation between an unsteady flow structure and the resulting signal generated by the impact of that flow structure with a solid surface, and may significantly impact research in the area of flow related structural acoustics.